

What planetary nebulae can tell us about jets in core collapse supernovae

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ABSTRACT

We compare the morphology of the core collapse supernova remnant (CCSNR) W49B with the morphology of many planetary nebulae (PNe), and deduce the orientation of the jets that shaped this CCSNR and estimate their energy. We find morphological features shared by some PNe and by the CCSNR W49B that are thought to be shaped by jets, such as a barrel-shaped main body. These morphological similarities are used to deduce that the jets were launched along the symmetry axis of the ‘barrel’, and to speculate that this CCSNR has two opposite lobes (or ears), that are too faint to be observed. The morphological similarities strengthen the suggestion that jets play a central role in the explosion of massive stars.

1. INTRODUCTION

Observations in recent years (e.g., Maund et al. 2007; Lopez et al. 2011, 2013, 2014; Milisavljevic et al. 2013; González-Casanova et al. 2014; Fesen & Milisavljevic 2016; Inserra et al. 2016) suggest that jets play a role in core collapse supernova (CCSN) explosions of many massive stars. Long gamma ray bursts (GRBs) that are thought to be emitted by jets (e.g., Woosley 1993; Shaviv & Dar 1995; Sari & Piran 1997), and in some cases are accompanied by Type Ic supernovae (e.g., Cano et al. 2016), further support the notion that jets play a role in many CCSNe.

Several arguments and numerical simulations suggest that the collapse of a pre-explosion rapidly rotating core leads to the formation of two opposite well collimated jets (e.g. Khokhlov et al. 1999; MacFadyen et al. 2001; Höflich et al. 2001; Woosley & Janka 2005; Burrows et al. 2007; Couch et al. 2009, 2011; Takiwaki & Kotake 2011; Lazzati et al. 2012; Mösta et al. 2014; Bromberg & Tchekhovskoy 2016; Gilkis 2017; Nishimura et al. 2017). The condition of a rapidly rotating core requires that a stellar binary companion enters the envelope and spirals-in to the core. Therefore, pre-explosion rapidly rotating cores are rare. It might be that jets in CCSNe are more common than the constraints imposed by this condition (e.g. Grichener & Soker 2017).

It is possible that most, or even all, CCSNe are exploded by jets in what is termed the jet feedback mechanism (JFM; Gilkis et al. 2016; Soker 2016). When there is a large amount of pre-collapse angular momentum, the mass accreted on to the newly born neutron star or black hole forms an accretion disk that launches opposite jets in a well define axis, as described in the studies cited above. When the pre-collapse core rotates slowly, the angular momentum of the accreted gas is likely to be stochastic (Gilkis & Soker 2014, 2015), and intermittent accretion disks or belts might formed (Schreier & Soker 2016), and might launch jets with stochastically varying directions; this is termed the jittering jets mechanism (Papish & Soker 2011, 2014a,b).

Castelletti et al. (2006) suggest that the CCSN remnant (CCSNR) Puppis A with a morphology that contains two opposite ‘ears’, was shaped by jets. Grichener & Soker (2017) extend the study to several other

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CCSNRs with ears. Under the assumption that the ears were shaped by jets that were launched during the explosion, Grichener & Soker (2017) calculated the energy of the jets. The typical energy of the shaping jets is $\approx 10\%$ of the kinetic energy of the CCSNR. This is compatible with the last jet-launching episode in the jittering jets model.

Ears are observed also in supernova remnants (SNR) of Type Ia supernovae (SNR Ia). These were compared to the morphologies of ears in planetary nebulae (PNe), and lead to the conclusion that some SN Ia explode inside PNe (term SNIP; Tsebrenko & Soker 2015a,b), while others might be shaped by jets launched during the explosion (Tsebrenko & Soker 2013). Ears, and similar smaller and larger opposite lobes, in PNe are thought to be shaped by jets (e.g., Soker 1990; Sahai & Trauger 1998).

In this study we examine the morphology of CCSNR W49B (section 2) and compare it with the morphologies of several PNe (section 3). In section 4 we estimate the energy of jets that shaped the SNR. Like Lopez et al. (2011) and Lopez et al. (2013) we conclude that the CCSN was driven by jets, but we find the jets' direction to be perpendicular to the direction inferred by them (González-Casanova et al. 2014). We summarize in section 5.

2. THE SNR W49B

W49B is one of the brightest supernova remnant (SNR) in X-rays in the Galaxy with $L_x \approx 10^{38} \text{ erg s}^{-1}$ (e.g., Lopez et al. 2013 and references within). The H. E. S. S. Collaboration et al. (2016) detect a γ -ray source coincident with the SNR W49B. Some properties of the SNR W49B are summarized in Table 1.

Property	Value	Reference
Age	1000 - 4000 yr	A
Distance	$\sim 8 - 10 \text{ kpc}$	B
Progenitor mass	$\simeq 25M_{\odot}$	C
Hot dust ($151 \pm 20 \text{ K}$)	$7.5 \pm 6.6 \times 10^{-4} M_{\odot}$	D
Cold dust ($45 \pm 4 \text{ K}$)	$6.4 \pm 3.2 M_{\odot}$	D

Table 1: A: e.g., H. E. S. S. Collaboration et al. (2016); Miceli et al. (2006) and references within. B: Moffett & Reynolds (1994); Zhu et al. (2014) and references within the latter. C: An estimate zero-age main sequence mass of the progenitor (e.g., Maeda & Nomoto 2003; Nomoto et al. 2006; González-Casanova et al. 2014; Zhu et al. 2014). D: Zhu et al. (2014).

Previous studies of W49B show three morphological and spectral features that are not found in other Galactic SNRs.

1. Segregation of its nucleosynthetic products. The X-ray emission is elongated in a bar-like centrally shaped structure, with two plumes and is not homogeneously spread. In fact, the iron is missing in the west side while other elements (like silicon and sulfur) are relatively homogeneously distributed (for more details see Hwang et al. 2000; Miceli et al. 2006; Lopez et al. 2009a, 2013).
2. The X-ray spectrum indicates rapid cooling. Rapid cooling is uncommon in young SNR such as W49B (for more details see Ozawa et al. 2009; Lopez et al. 2013 and references within the latter).

3. Detected X-ray spectral lines from chromium and manganese that are products of silicon burning (for more details see Hwang et al. 2000; Miceli et al. 2006; Lopez et al. 2013).

There are two proposed scenarios to account for the properties of W49B, namely, a non spherical explosion of a massive star and an interaction of a spherical SN with an inhomogeneous ISM (e.g., Lopez et al. 2013; Zhu et al. 2014). Recent studies support the first scenario of a jet-driven CCSN explosion over the ISM scenario (Lopez et al. 2013; González-Casanova et al. 2014).

Keohane et al. (2007) suggest four distinguishing characteristics of a remnant of a jet-driven explosion of a massive star. (1) A double ‘T-shaped’ structure. This structure follows the path of the bipolar jets. (2) A non homogeneous spread of heavy elements which include higher abundance of heavy elements than a typical Type II SN due to the fact that the jets originate from inside the iron core. (3) A supermassive progenitor with strong stellar winds. (4) No trace/observation of a neutron star (NS).

According to Keohane et al. (2007) all of them are evident for W49B. Zhu et al. (2014) also mention similar morphology features that support the explosion scenario. The explosion scenario may account for inhomogeneous distribution of iron due to the fact that heavy element tend to be ejected along the polar axis. Khokhlov et al. (1999) who numerically studied the explosion of supernova caused by supersonic jets showed that the end result is a non-spherical supernova explosion with two polar directed jets. The composition of the jets must reflect the composition of the innermost parts of the star and should contain heavy and intermediate-mass elements. The interaction with the ISM is relevant for other sources (e.g., G292.0+1.8: Park et al. 2004) but it requires fine-tuning of the configuration of the cloud (Keohane et al. 2007).

The double ‘T-shaped’ structure mentioned by Keohane et al. (2007) is addressed by us as the ‘H-shaped’ morphology due to the fact that the legs of the ‘H’ are not symmetrical and can form either a ‘H’ shape (if both legs are observed) or a ‘T’ shape (if only one leg is observed). This is seen in Fig. 1 where the two legs of the H do not have the same size, and therefore they can account for the T shape feature. We show the versatility of the asymmetric ‘H-shaped’ of SNR W49B in Fig. 1 that presents X-ray images of three elements.

We do not accept all four properties of SNRs formed by jet-driven CCSN as listed by Keohane et al. (2007). We do not think that H or T shapes are the main outcome of the operation of jets. We rather adopt the view, which is based, among others, on properties of PNe, that the most prominent feature of strong jets is the presence of two opposite ears or lobes (e.g., Grichener & Soker 2017). We further adopt the view that the non-negligible amount of angular momentum of the exploding star might leave behind a rotating neutron star that is a pulsar or a magnetar, as seen in some CCSNRs with two opposite small lobes (termed ears) that are thought to be shaped by jets Grichener & Soker (2017).

3. COMPARISON WITH PLANETARY NEBULAE

The SNR W49B has a unique morphology among CCSNRs, but a morphology that is common among PNe, in particular these four features. (1) The general barrel shaped of W49B is observed in the central part (the main body) of many PNe. The jets in PNe are thought to be propagating along the symmetry axis of the barrel-shaped region. (2) In many cases, PNe that have a general barrel morphology similar to that of the main body of W49B, have one or more pairs of lobes (ears) along the direction of the jets. (3) An ‘H-shaped’ feature is observed in many PNe. In PNe the legs of the ‘H-shaped’ structure are thought to be parallel to the axis of the jets. (4) Dense filaments as observed in the SNR W49B are also observed in

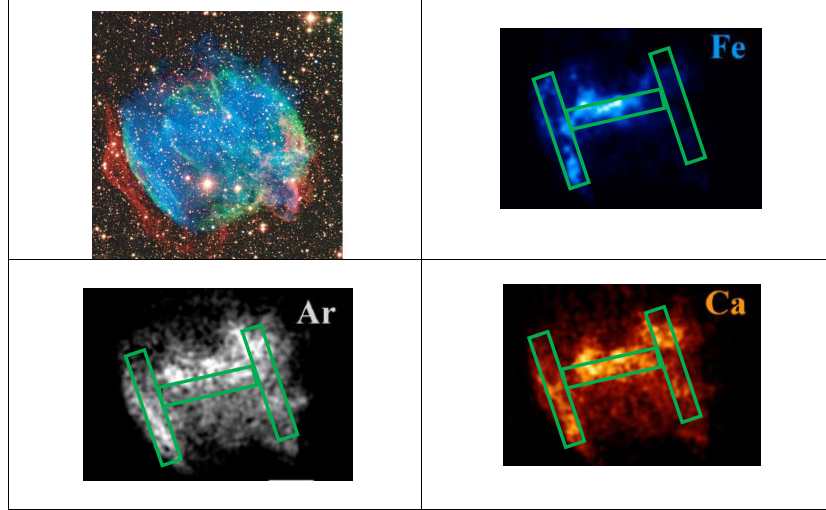


Fig. 1.— The morphology of SNR W49B (upper left; from Chandra website: <http://chandra.harvard.edu/photo/2013/w49b/>), and the ‘H-shaped’ morphology in X-ray lines of Fe xxv (upper right), Ar xvii and Ar xviii (lower left), and Ca xix and Ca xx (lower right); the later three images are from Lopez et al. (2013). The ‘H-shaped’ morphology is marked in green.

some PNe.

These four morphological features are presented in Figure 2, both for the SNR W49B and for three PNe. Filaments are shown for PN G138.1+04.1 (Sh 2-200), a barrel-shaped inner region, lobes and an ‘H-shaped’ are shown for PN G298.2-01.7 (He 2-76) and PN G317.1-05.7 (He 2-119). The center of each lobe (more or less) is marked by an ‘X’.

We have scanned two databases of PN images, those of Parker et al. (2016) and of Balick (starting with Balick 1987 and extended to PNIC: Planetary Nebula Image Catalogue), and found that many PNe exhibit similar morphology features to those of the SNR W49B. We present nine such PNe in Fig. 3. We arrange these PNe by their most prominent feature, according to three features, barrel+lobes, filaments, and H-shape.

The line connecting the two ‘H-legs’ in PNe is considered to be an equatorial ejected material rather than a jet. It can be a ring (or torus) viewed edge-on, or a segment of a ring. We suggest the same for the CCSNR W49B. One good case of such a PN is Abell 41 (PN G009.6+10.5) that was analyzed by Jones et al. (2010). In the left panel of Fig. 4 we present the [NII] 6584Å. A clear equatorial ring is observed. Jones et al. (2010) analyzed the structure of Abell 41, and built a synthetic model for its structure. When viewed edge-on (inclination angle of 90°), a dense bar is seen extending perpendicular to the symmetry axis. In PNe the symmetry axis is along the axis of the jets. Namely the dense bar is perpendicular to the jets.

Based on the strong similarities between the morphology of SNR W49B and many PNe, we suggest that this SNR was shaped by two opposite jets launched from the center during, or shortly after, the explosion. We further suggest that, like in PNe, the symmetry axis of the jets is along the symmetry axis of the barrel-shaped inner region, namely, parallel to the legs of the H-shaped region seen in different X-ray lines. Our proposed axis of the jets is perpendicular to the jets’ axis as proposed by Lopez et al. (2013) and Keohane et al. (2007). We take the structure these papers refer to as jets, to be an equatorial dense gas, as seen in many PNe.

Although our conclusion is based on a qualitative comparison of the CCSNR W49B with PNe, we feel it stands on solid ground. There are similarities between bipolar structures carved by jets in PNe and many other astrophysical objects, such as X-ray deficient bubbles in cooling flow clusters (Soker & Bisker 2006), ears in SNR of Type Ia SNe (Tsebrenko & Soker 2015b), and nebulae of massive stars, e.g., Eta Carinae (e.g., Morse et al. 1998). As these and other papers show, the similarities go much beyond the morphological similarities, and extend to physical processes, including the interaction of the jets with the ambient gas. The orientation of the jets in W49B has implications on the explosion mechanism of the SN. In particular, our suggested jets’ orientation hints that the jets played an important role in the explosion, as we argue next.

4. THE ENERGY OF THE JETS

In Fig. 5 we mark the suggested lobes that were inflated by the jets we are claiming for in the study. We suggest these lobes based on comparison to PNe. When viewing the PNe (see figure 3) we can generally say that the lobes diameter is of the same order as the barrel radius. If we extrapolate this notion to the SN W49B we can suggest that with deeper observation, possibly at different wavelengths also, the lobes might be revealed.

Our estimate, based on the structure of many PNe, that the distance of the tip of the lobe from the center is twice the distance of the edge of the barrel-shaped region from the center is a crude assumption

(each dashed yellow line is half the length of the solid yellow line). Nonetheless, it gives us the possibility to estimate the lobes energy as we anticipate based on the morphologies of many PNe.

We follow Grichener & Soker (2017) and estimate the energy of the suggested lobes with the same assumptions they have made (we will not repeat the description of the technique here). We find that the combined kinetic energy of the two assumed lobes is about 20 – 25% of the energy of the entire SNR shell. Since not all the energy of the jets will end up in the lobes, we crudely estimate that the jets that inflated the lobes and shaped the CCSNR into a barrel shape had a kinetic energy that amounts to about one quarter to one third of the energy of the entire CCSNR.

This energy is more than twice as large as the energy of the jets in the eight CCSNRs studied by Grichener & Soker (2017). It seems that the jets were strong enough to disperse the lobes/ears of W49B to the degree that they are too faint to be detected. The lobes might be larger than what we assumed in drawing Fig. 5, and therefore the energy of the jets might be larger even than the value we deduce here.

5. SUMMARY

We compared the morphology of the CCSNR W49B with those of many PNe, 13 of which are presented here in figs. 2 - 4. Although this comparison is qualitative, we consider the following conclusions to be robust and with important implications.

- (1) Based on the similar structure of the barrel-shaped main inner part of W49B with many PNe, we deduced that the symmetry axis of W49B is along the symmetry axis of the ‘barrel’, as marked in Fig. 2.
- (2) The shaping mechanism of the PNe with similar structures is thought to be jets. We deduce that W49B was shaped by two opposite jets launched along the symmetry axis of the ‘barrel’. This direction is perpendicular to earlier suggestions for the jets’ direction (e.g., Keohane et al. 2007; Lopez et al. 2013).
- (3) In most PNe two opposite lobes/ears protrude along the symmetry axis. We assumed that such lobes/ears exist in W49B, but that they were dispersed and hence too faint to be observed. We very crudely (and conservatively) estimated that the energy of the jets that inflated these lobes/ears was about one quarter to one third of the energy of the entire CCSNR.

One of the expectations of the JFM explosion mechanism of CCSNe is that last segments of the jets to be launched will expand to large distances. The reason is as follows (see also Grichener & Soker 2017). According to the JFM, as long as accretion process continues, jets are launched (assuming there is enough angular momentum to form an accretion disk or an accretion belt; Schreier & Soker 2016). The accretion process continues as long as there is bound core material, as is required for a negative feedback mechanism. After the outer parts of the core are completely ejected some in-flowing gas, that was already on its way in, is accreted and the final jet-launching episode takes place. The gas in this last episode does not encounter dense gas in the core and envelope anymore, as the core and envelope have been ejected. The jets expand freely and interact with the exploding material outside the star, during the expansion phase. Such jets can form ears (Tsebrenko & Soker 2013).

The similarity of the morphology of W49B with those of many PNe further support the call for a paradigm shift from neutrino-driven to jet-driven core-collapse supernova mechanisms.

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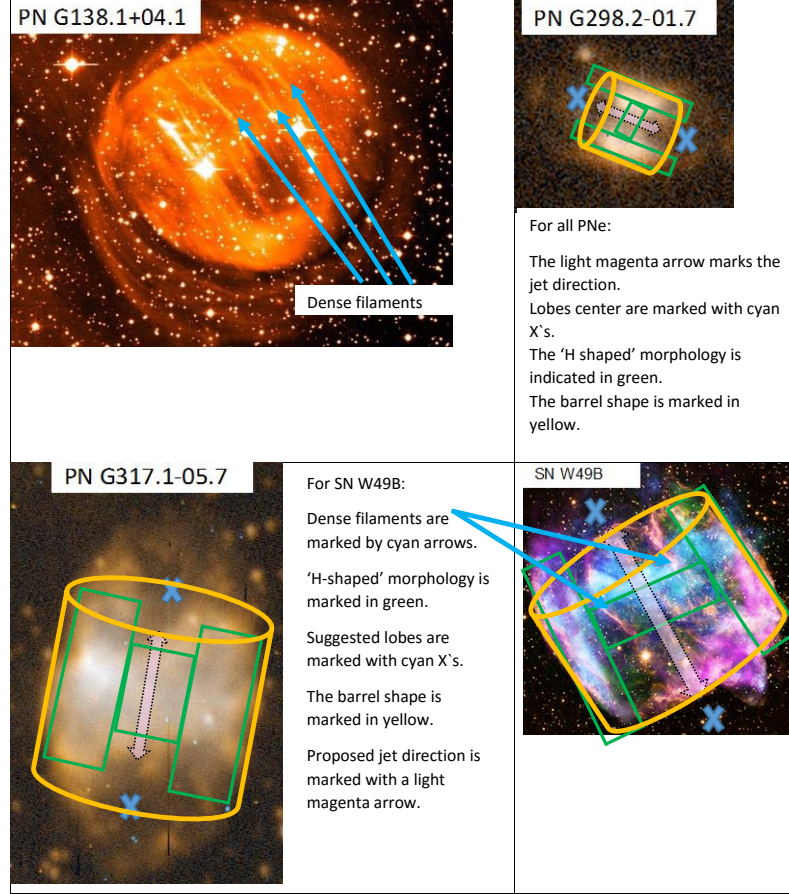


Fig. 2.— Comparing the morphologies of the CCSNR W49B (credit the Chandra website <http://chandra.harvard.edu/photo/2013/w49b/>) and three PNe. PN G138.1+04.1 (Sh 2-200; credit Balick 1987; Corradi et al. 2003) contains many dense thin filaments. The PNe PN G298.2-01.7 (He 2-76; credit Balick 1987; Górny et al. 1999) and PN G317.1-05.7 (He 2-119; credit Balick 1987; Górny et al. 1999) possess a barrel-shaped inner region (marked in yellow), an 'H-shaped' bright region (marked with green) and lobes. The approximate center of each lobe is marked by a cyan 'X'. The direction of the jets as taken in modeling PNe is marked in light magenta, and is parallel to the H-shaped legs. The yellow-shape barrel is schematic and does not indicate the inclination of the barrel-shaped nebular part.

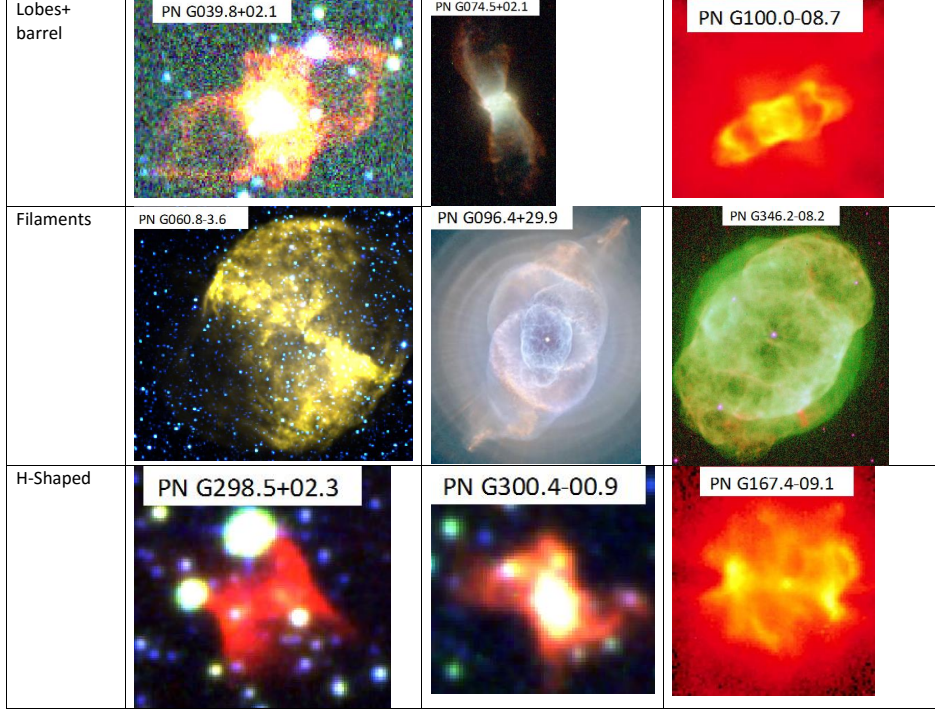


Fig. 3.— Nine PNe that share one or more morphological features with the SNR W49B. We list the PNe according to the most prominent morphological feature, as indicated in the figure. The PNe with their common names and credits are as follows. PN G 039.8+02.1 (PN K 3-17; credit: A), PN G074.5+02.1 (NGC 6881; B), PN G100.0-08.7 (Me 2-2; C). PN G060.8-03.6 (M-27; A), PN G096.4+29.9 (NGC 6543; D), PN G346.2-08.2 (IC 4663; B), PN G298.5+02.3; A), PN G300.4-00.9 (Hen 2-84; A), PN G167.4-09.1 (K 3-66; C). Credits:

[A] HASH catalog - (Parker et al. 2016).

[B] HST archives from PNIC catalog - (Balick 1987).

[C] Sahai & Trauger (1998).

[D] Hubblesite from PNIC catalog (Balick 1987) Corradi and Tsvetanov go 9026 *http* : [//hubblesite.org/gallery/album/nebula_collection/pr2004027a](http://hubblesite.org/gallery/album/nebula_collection/pr2004027a).

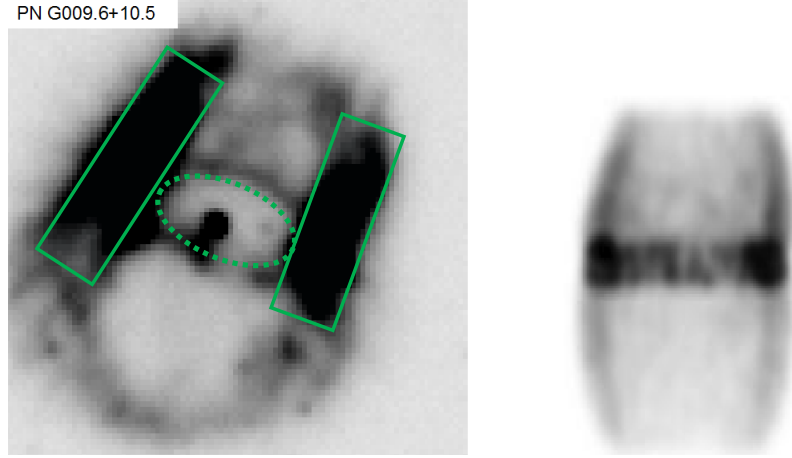


Fig. 4.— The PN Abell 41 (PN G009.6+10.5). The left panel is an $[\text{NII}]$ 6584\AA image. The right panel presents a synthetic model for the emission in this line from Abell 41 displayed at an inclination of 90° , namely, the symmetry axis is on the plane of the sky and vertical in the image. Both panels are taken from Jones et al. (2010). On the left panel we added marks of the ring and the two legs of the H-shaped region.

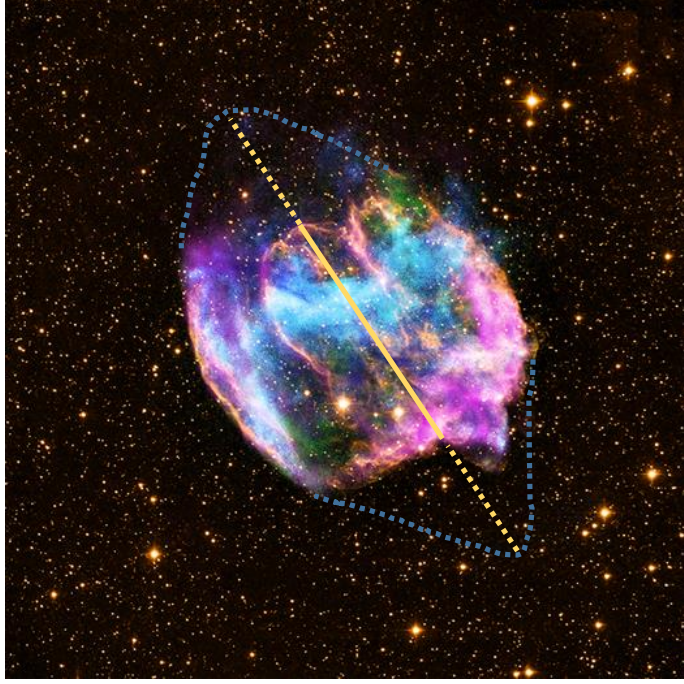


Fig. 5.— The figure shows SN W49B with the suggested symmetry axis marked with a yellow line. The suggested lobes are marked by their hypothetical boundaries with dotted cyan line. The suggested lobes have a diameter marked with a dotted yellow line, the length of which is equal to half the length of the solid yellow line. Credit: Chandra website (<http://chandra.harvard.edu/photo/2013/w49b/>).